New results DAMIC at Snolab
Looking for dark matter 6800 feet underground

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⋆DAMIC Collaboration: Fermilab, U Chicago, U Zurich, Snolab, U Michigan, UNAM, FIUNA, CAB, UFRJ, U Paris VI & VII

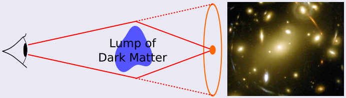
What will you see during this talk

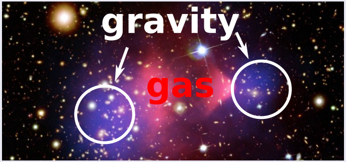
- 2 recent Dark Matter search results (one new and world best)
- 1 calibration result that has implications beyond this experiment
- 1 novel technique to measure isotopic abundance of ^{32}Si
- a hint of things to come

Observational evidence of Dark Matter (DM)

Lots of Observational evidence

- Galactic Rotation Curves
- Galaxy Clusters Dynamics
- Strong Gravitational Lensing
- The Bullet Cluster
- Large-Scale Structure Formation
- Big Bang Nucleosynthesis





DM may not exist, but if it doesn't we have a lot to explain..

Candidates

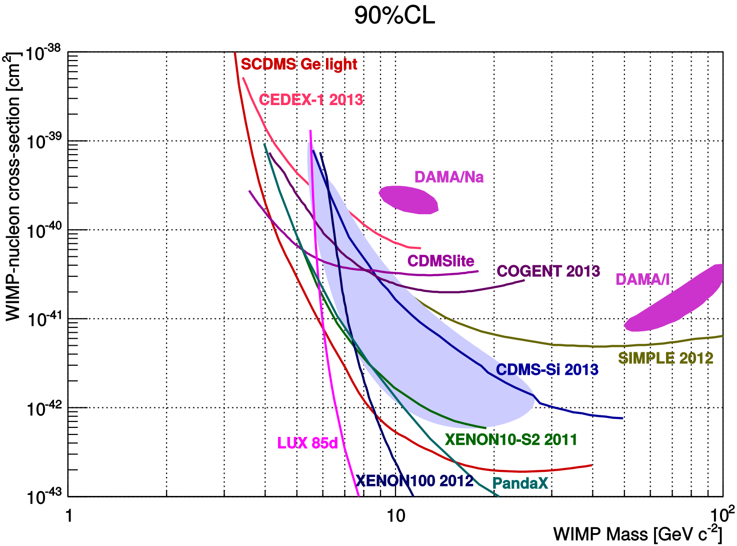
Some possibilities that have been proposed

- Weakly-interacting massive particles (WIMPs)
- Sterile neutrinos
- Axions
- Anything else

Very active area

More than 200 papers on light DM in 2015!

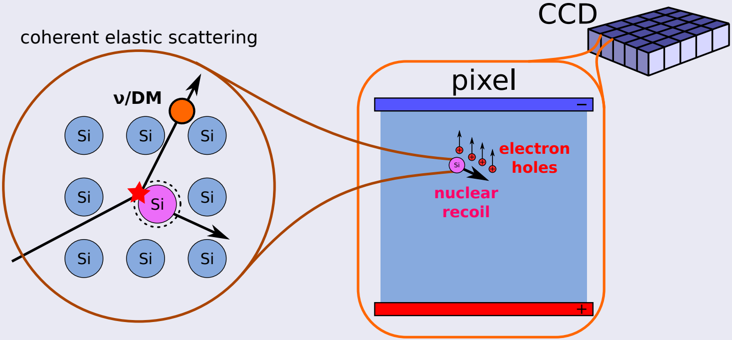
Motivation


90%CL
WIMP-nucleon cross-section [cm^2]
10^{-38}
10^{-39}
10^{-40}
10^{-41}
10^{-42}
10^{-43}
1
10
10^2
WIMP Mass [GeV c^{-2}]
SCDMS Ge light
CEDEX-1 2013
DAMA/Na
CDMSlite
COGENT 2013
DAMA/I
SIMPLE 2012
CDMS-Si 2013
XENON10-S2 2011
LUX 85d
XENON100 2012
PandaX

Goal: lower the energy threshold in Si detectors

Detect coherent DM-nucleus interactions by measuring the ionization produced by the nuclear recoils

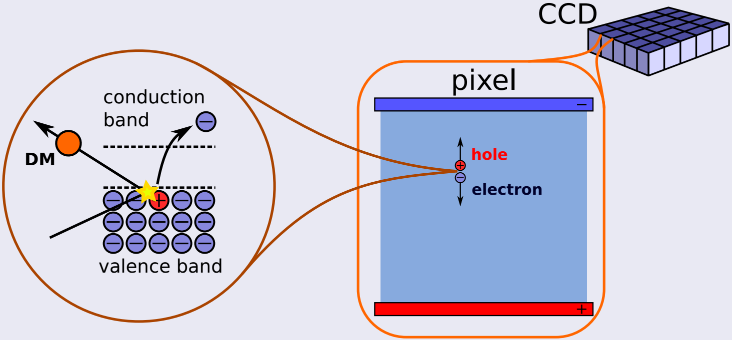
Idea: use CCDs as target and record the ionization produced



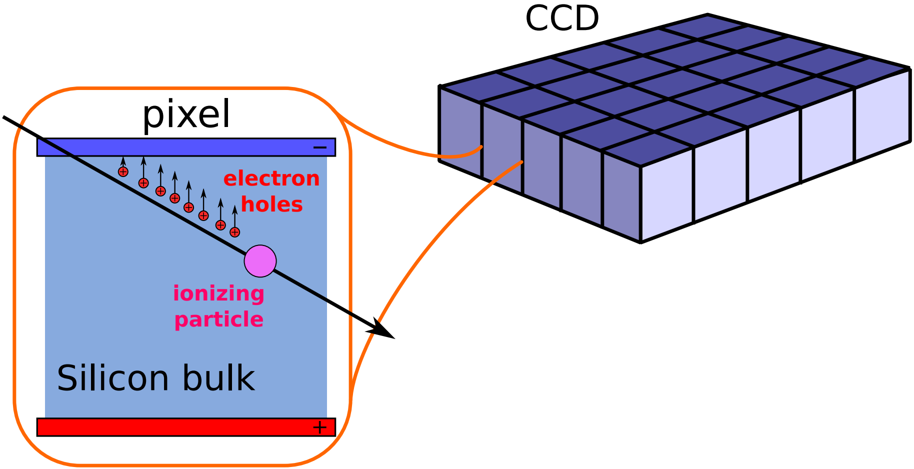
Goal: lower the energy threshold in Si detectors

Detect DM-e interactions by measuring the ionization produced by the electron recoils. More on this later..

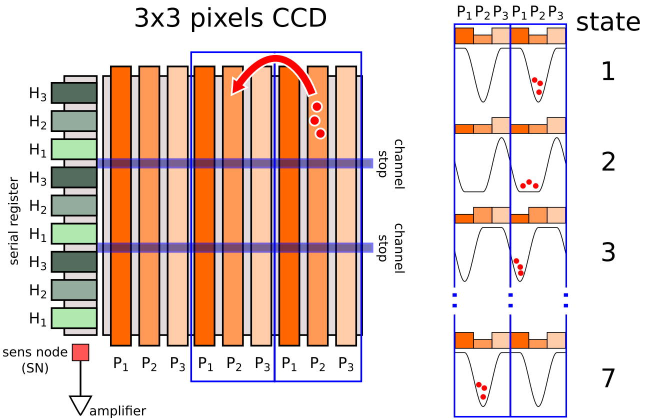
Idea: use CCDs as target and record the ionization produced



CCD: charge generation

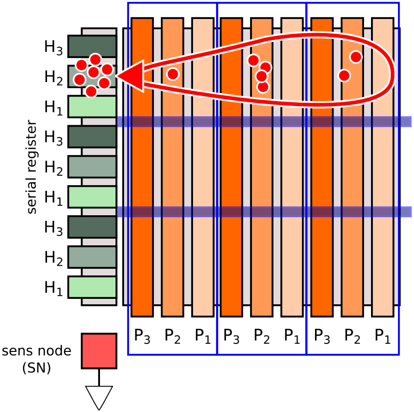


CCD: readout



capacitance of the system is set by the Sens Node: C=0.05pF$\rightarrow$ 3μV/e

Hardware Binning

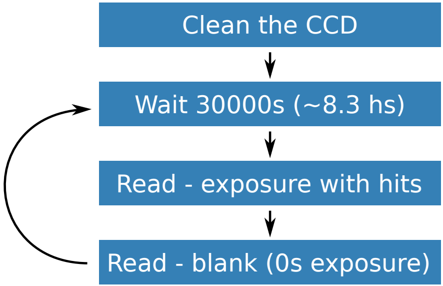


- Every readout introduces a $2e^-$ noise
- The CCD allows you to add charge in the sensor (binning) and then readout many pixels as a single one
- This improves signal to noise, effectively increasing the efficiency at low energy

$$\mathbf{S/Noise} = \frac{\mathbf{Q}}{\mathbf{N_{reads}}}\sigma$$

Reading the charge in less pixels is good!

CCD: readout - typical operation for DM searches



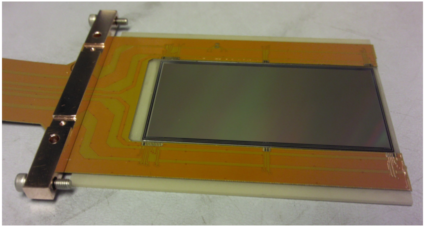
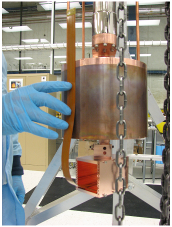
We take long exposures to minimize the number of readouts. The exposure is eventually limited by the dark current.

The blank images provide an excelent measurement of the background produced by readout

Detectors:

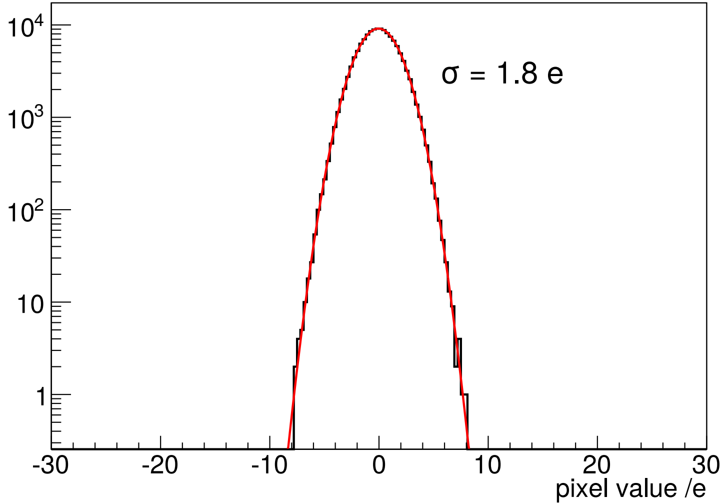
We use scientific CCDs developed by LBNL microdectors group

- pixel size of 15 μm
- 10x/27x thicker than most CCDs (250/675 μm)
  - up to 5.5 gr per CCD
  - diffusion $\rightarrow$ 3D rec $\rightarrow$ rejection of surface events
- CCDs cooled to 150 K to achieve readout noise RMS $\sim 2\ e^{-}$
- Energy threshold of $\sim$0.05 keVee

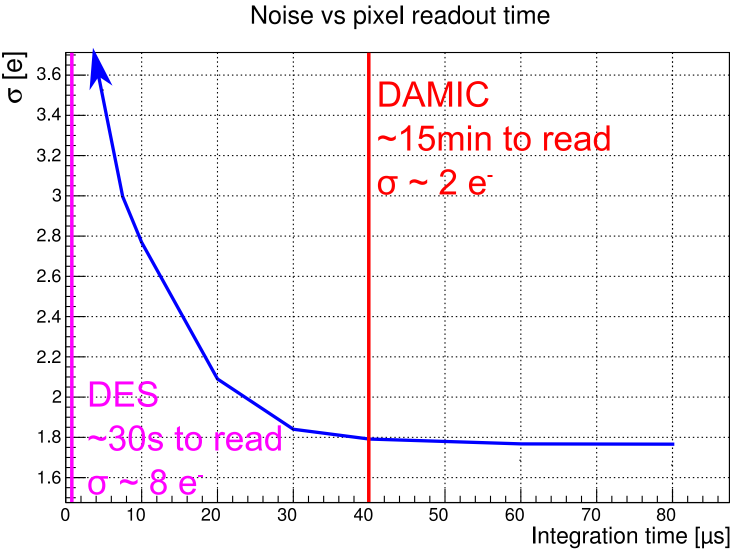




Fermilab

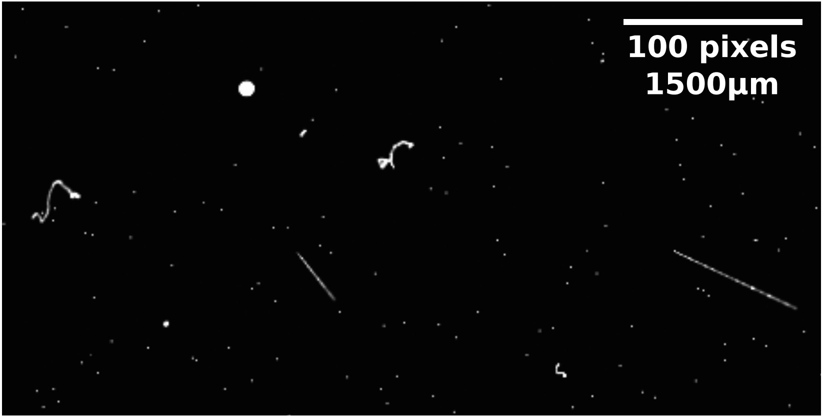
Readout Noise: empty pixels distribution



Readout Noise:

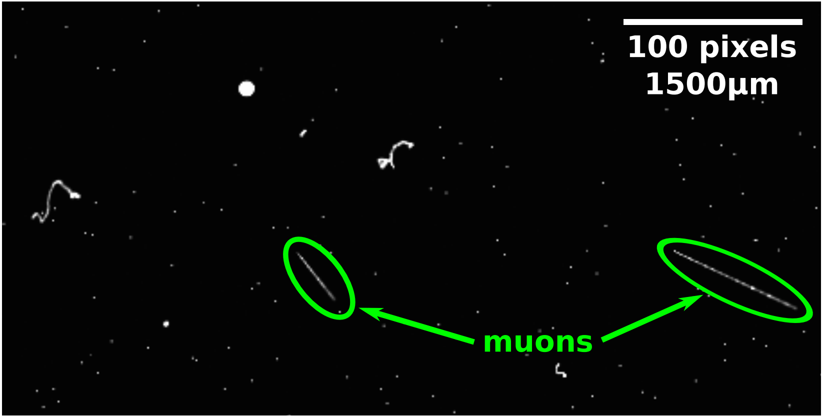


Particle ID



Data taken at Fermilab (sea level, no radiation shielding, expo ∼1min)

Particle ID



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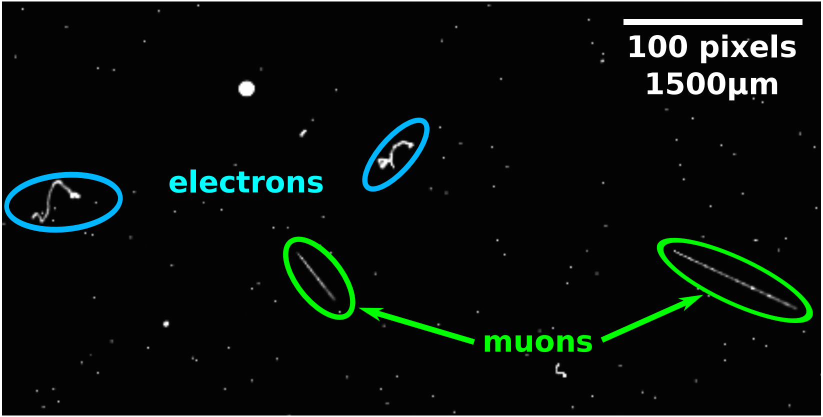

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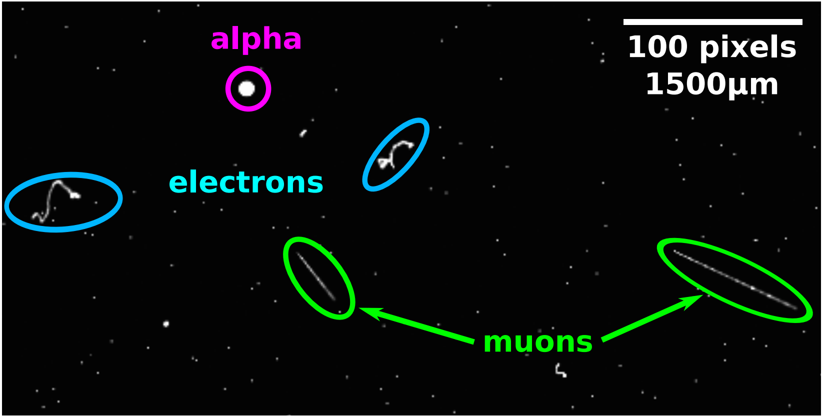

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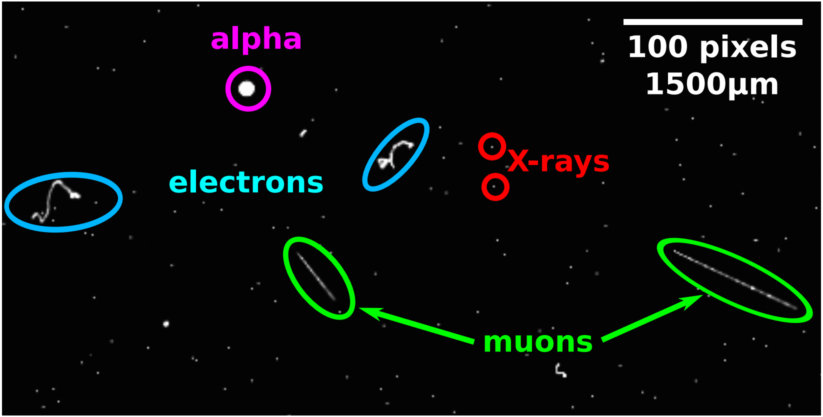

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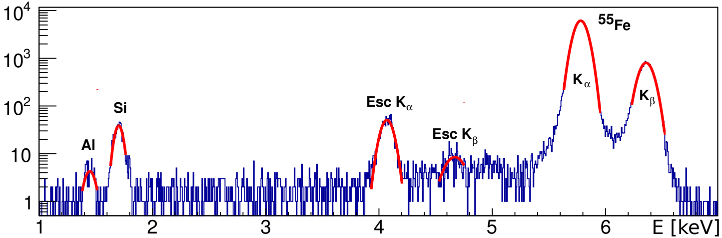
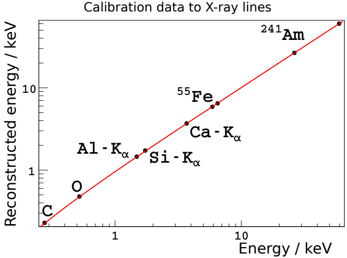
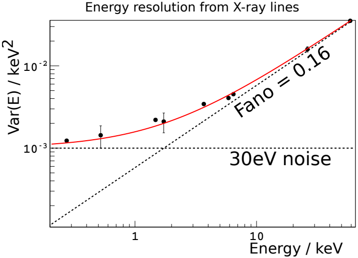
Energy calibration using X-rays







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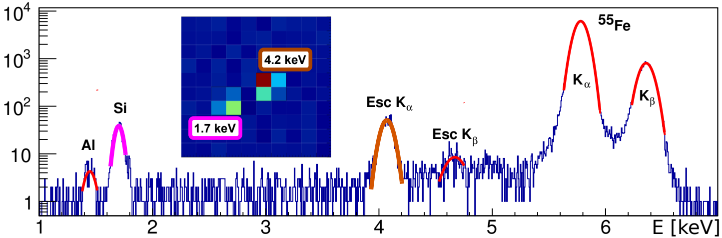
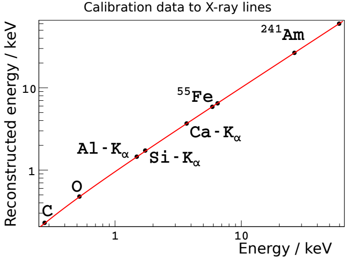
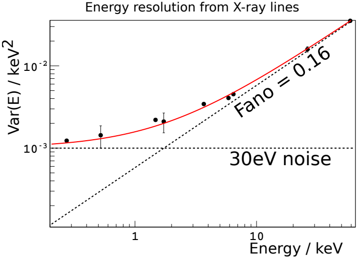
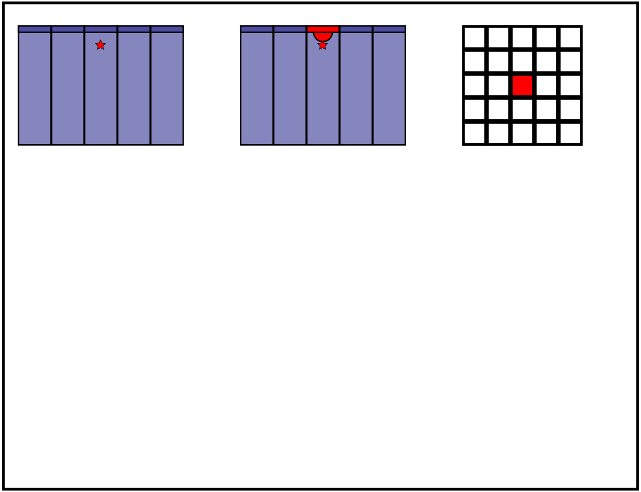






Diffusion



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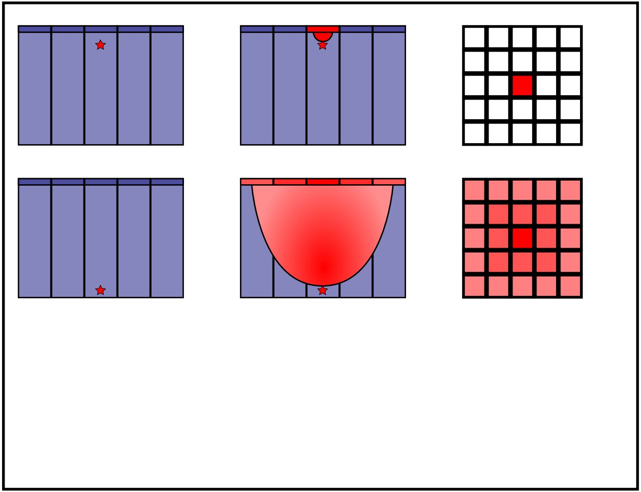
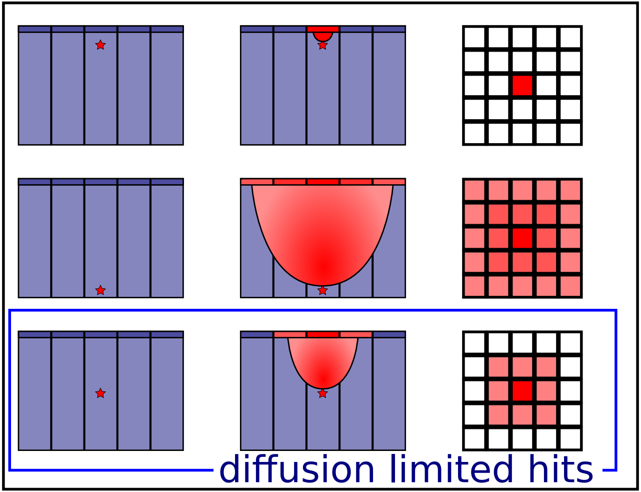
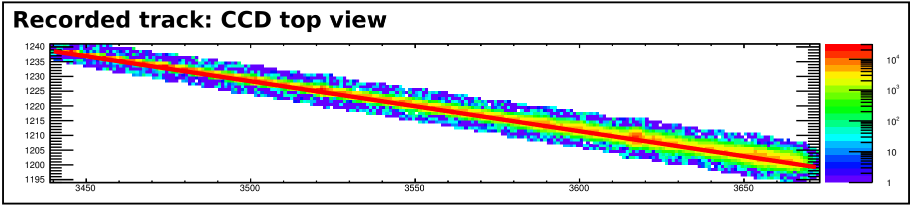
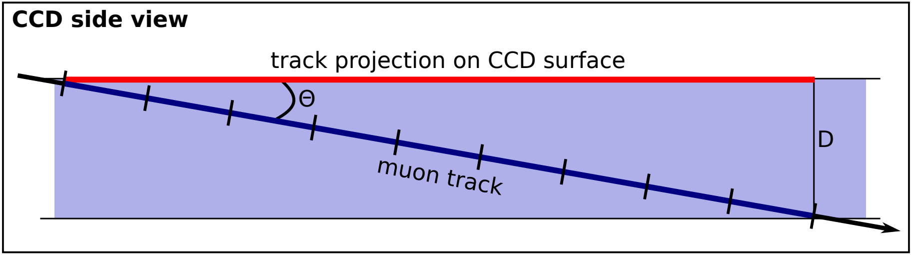


Diffusion



Measuring diffusion





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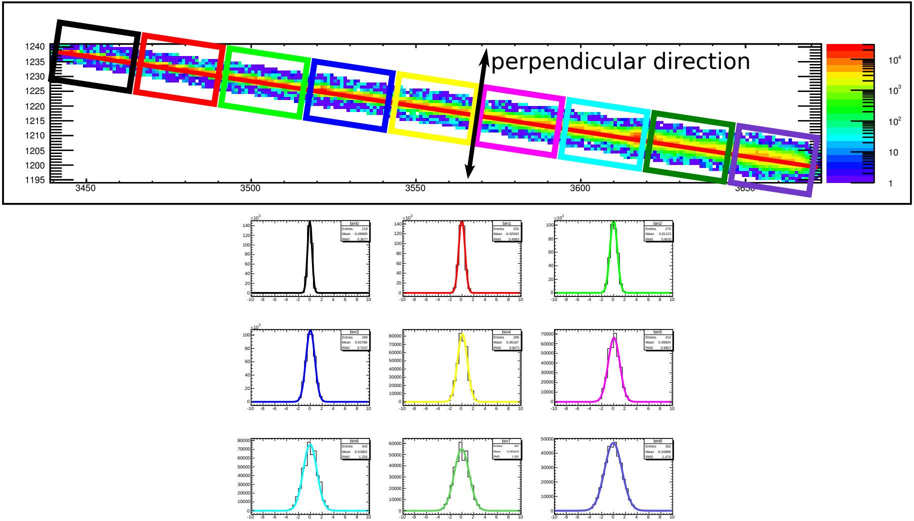

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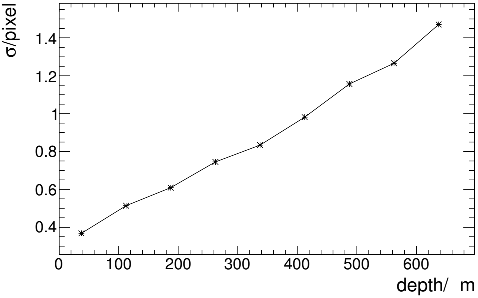
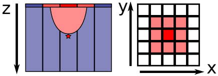
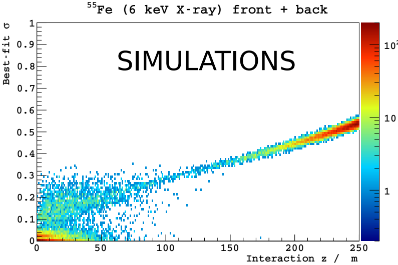


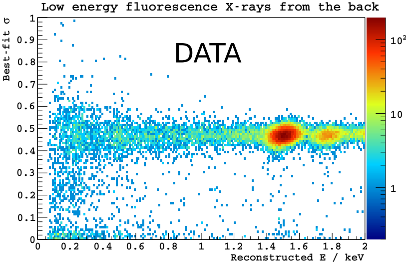
Diffusion can be measured as a function of the interaction depth.
No need to rely on models.

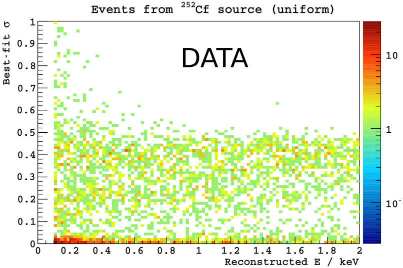
3D reconstruction of low energy (point like) like events

We fit to the radial spread of the cluster to estimate its position in z within the CCD bulk





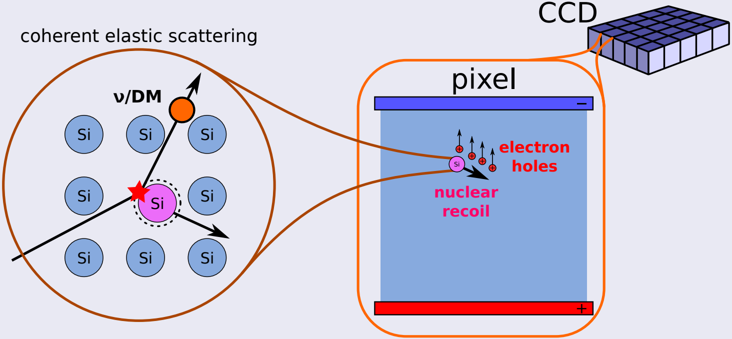




Nuclear recoil ionization efficiency

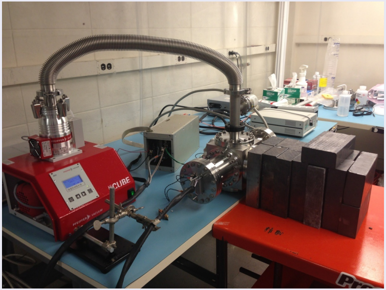
Quenching factor / nuclear recoil ionization efficiency

It's critical to know/measure the fraction of the nuclear recoil kinetic energy that goes into ionization (which is the only thing that we can see)



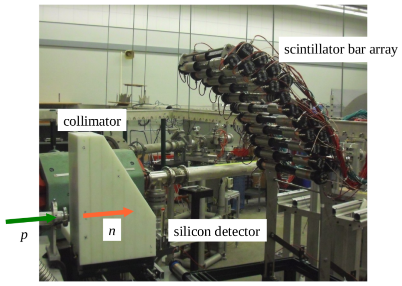
Nuclear recoil calibration program

Sb/Be source



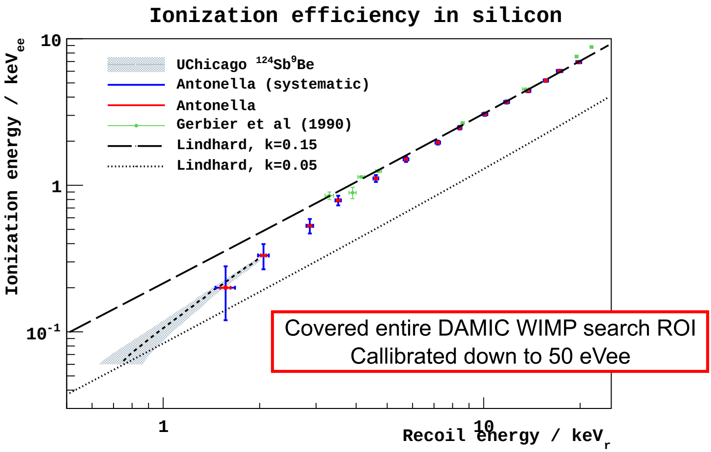
- Photo-neutron source at U. of Chicago
- 0.7 - 2 keV NR

Antonella (Fermilab)



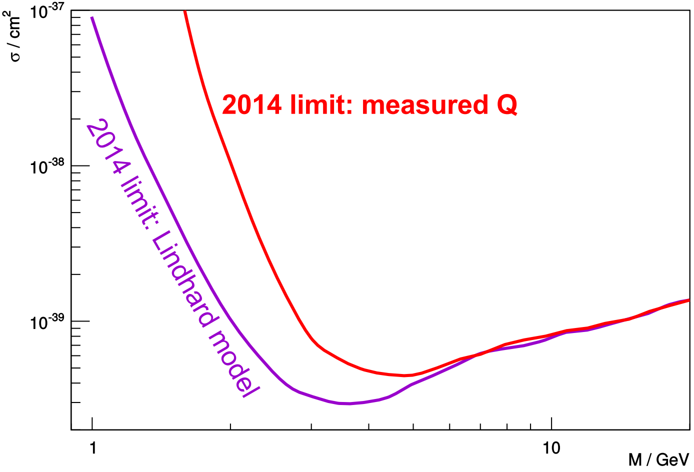
- Neutron beam at U. of Notre Dame
- 2 - 20 keV NR

Nuclear recoil calibration



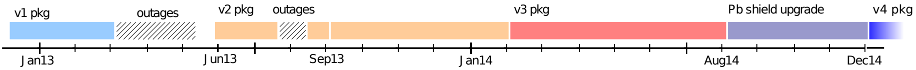
Discrepancy with Lindhard model below 5 keVee

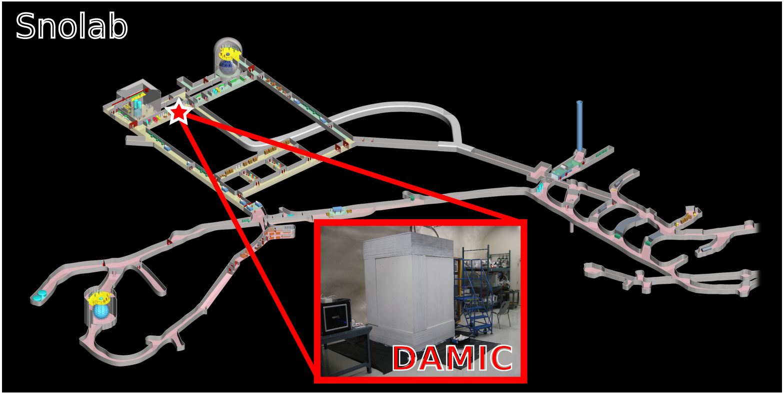
2014 run (DAMIC-2014): limit reanalysis



The quenching model has a huge impact on the sensitivity at low masses

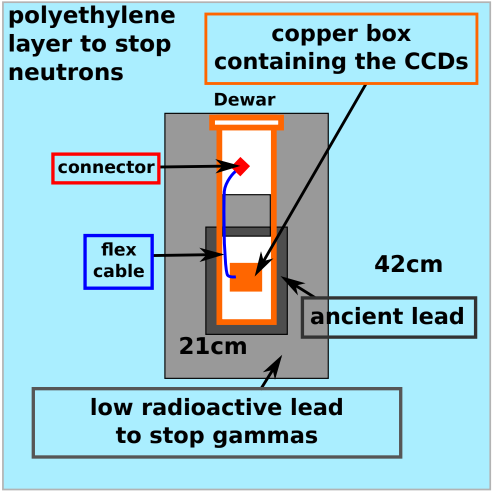
DAMIC @Snolab (installed Dec12)

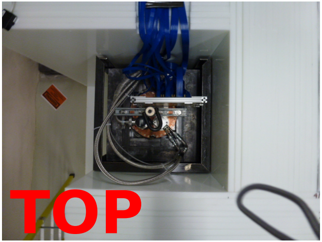




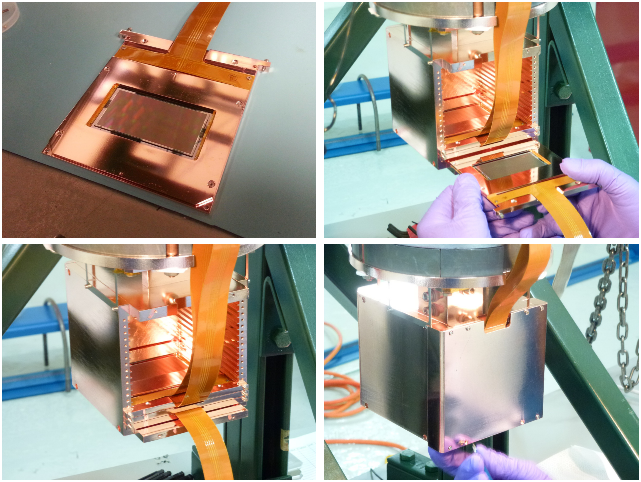
Installed at Snolab: 2km of norite overburden → 6000m water equivalent

DAMIC detector: shielding





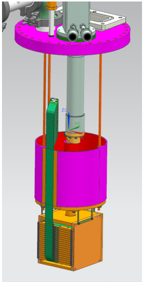
DAMIC detector

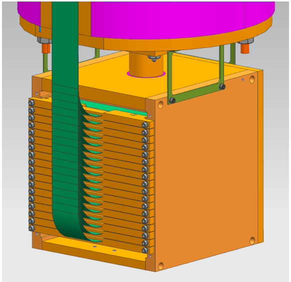


DAMIC100 @Snolab

Currently deploying 100 g of active mass. 2 (out of 18) already installed.

- 10/18 detectors ready to be deployed. **Commissioning on Apr-2016**
- So far we focused on understanding the activity of the inner materials to get full advantage of the mass increase.
- We still managed to collect a small sample of WIMP search data..

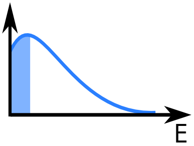




Background from Silicon: could be a limiting factor

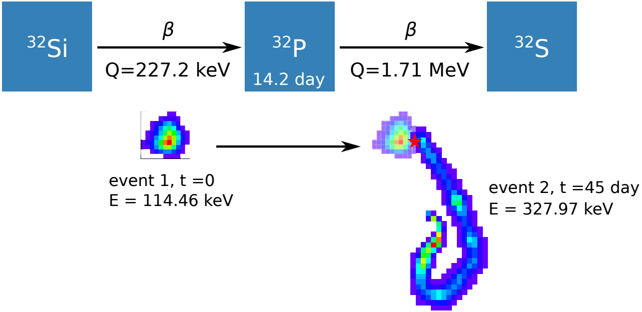
There is a long lived radioactive silicon isotope that is cosmogenically produced in the interaction of cosmic rays with atmospheric argon and other elements

Low energy electrons from β decays could be a significant background in silicon



Background from Silicon: candidate ^{32}Si event

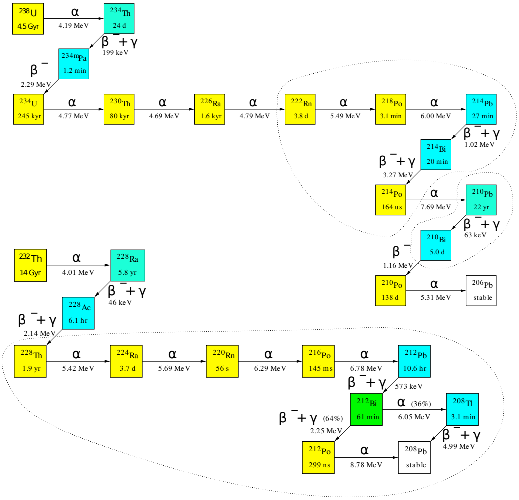
The precise position reconstruction in the CCD allows the study of spatial coincidences to measure and veto ^{32}Si events in the CCD



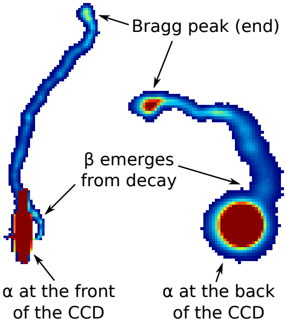
The pixelation of the DAMIC detector allows us to reject this background.
This is a unique capability of the DAMIC sensors.

Measured ^{32}Si decay rate: 80^{+110}_{-65} (95% CI) (arxiv:1506.02562)

U/Th decay chains

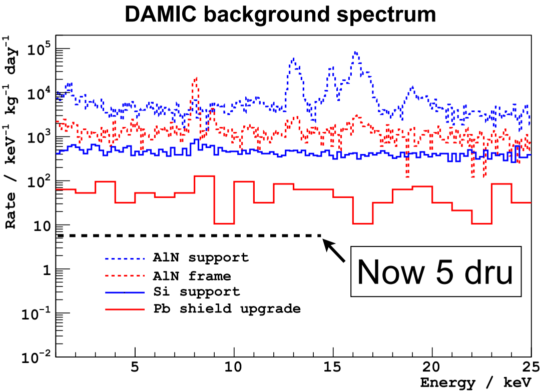


REAL EVENTS



Radioactive elements can be identified and spatially located by looking at $\alpha - \alpha$ and $\alpha - \beta$ coincidences.

2015 campaign: tracking backgrounds



In production mode

Converged on package design and materials

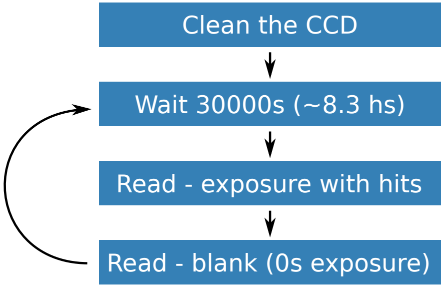
10/18 detectors tested and ready for deployment

Will commission during April 2016

WIMP search

Although during 2015 we dedicated most of the time to identify the backgrounds and screen materials we where a able to acquire a small sample of WIMP search data to test and develop our analysis framework

CCD: readout - typical operation for DM searches



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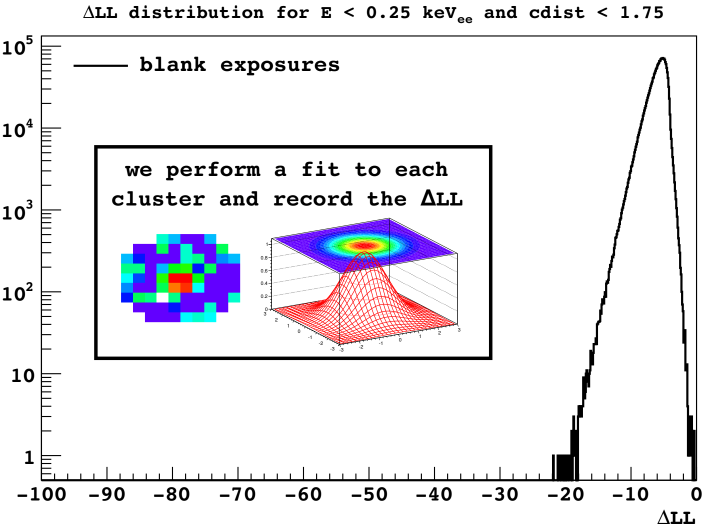
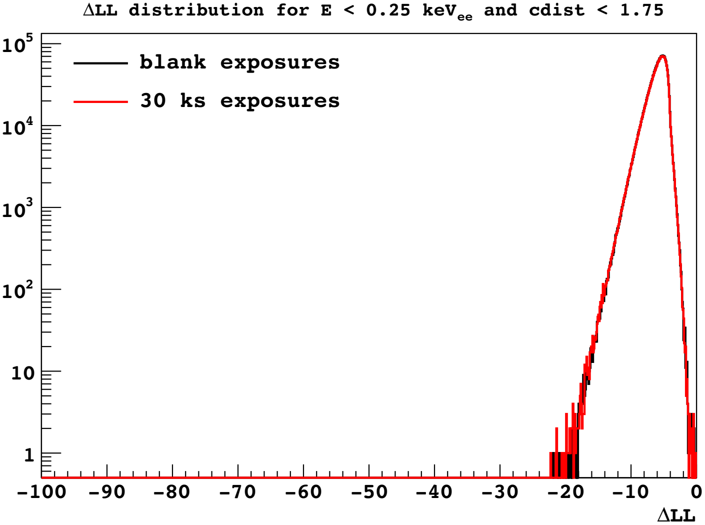
Data Analysis



Data Analysis



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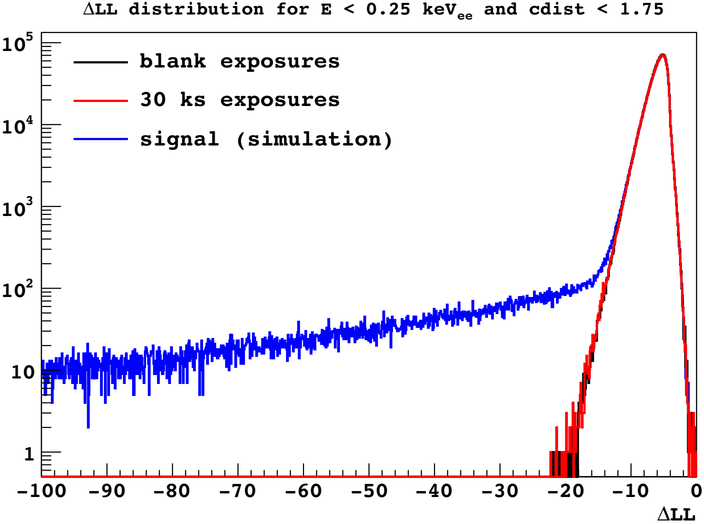
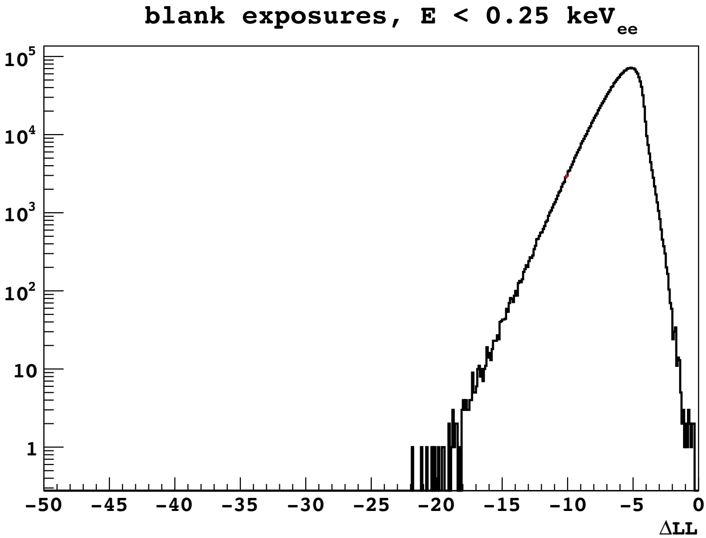


Data Analysis: events selection - quality cut



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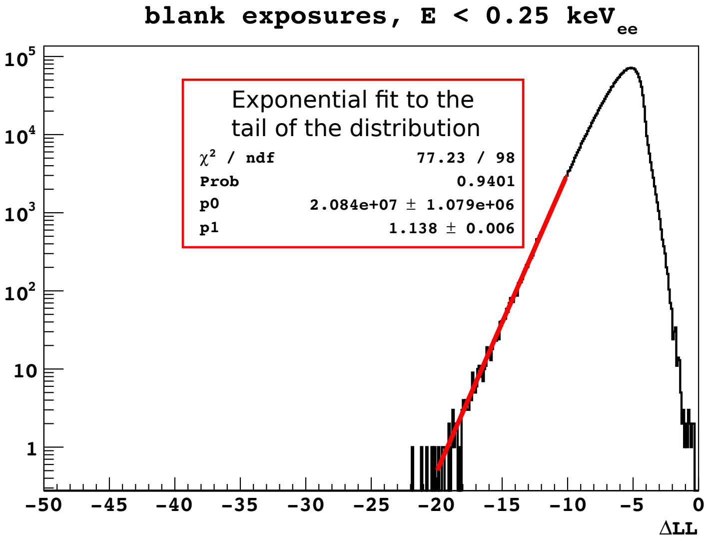

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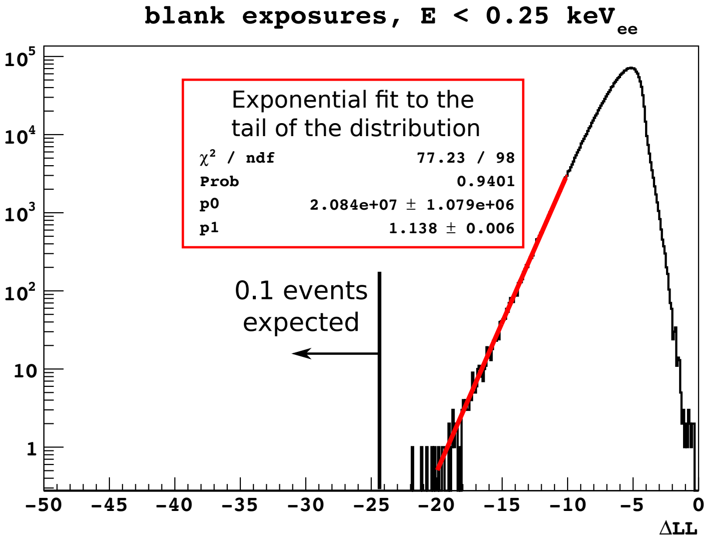
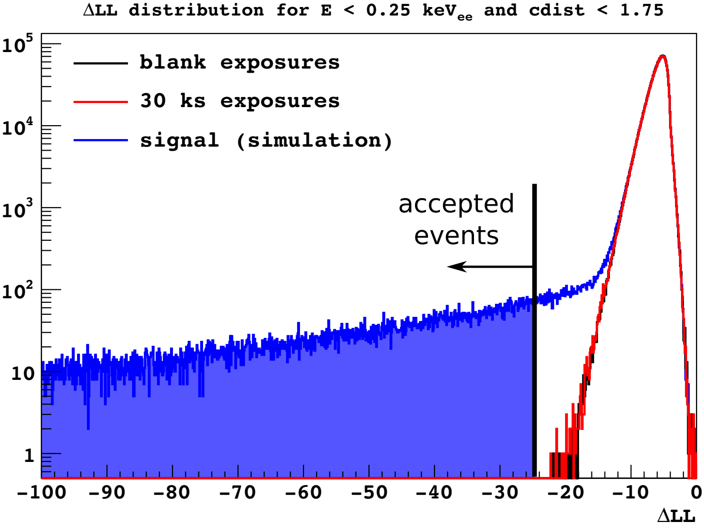
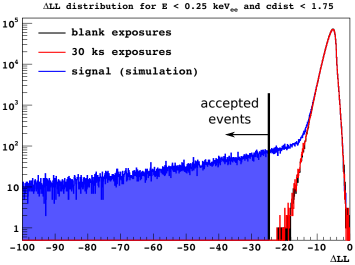
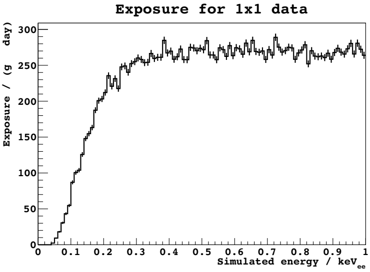


Data Analysis: events selection - quality cut



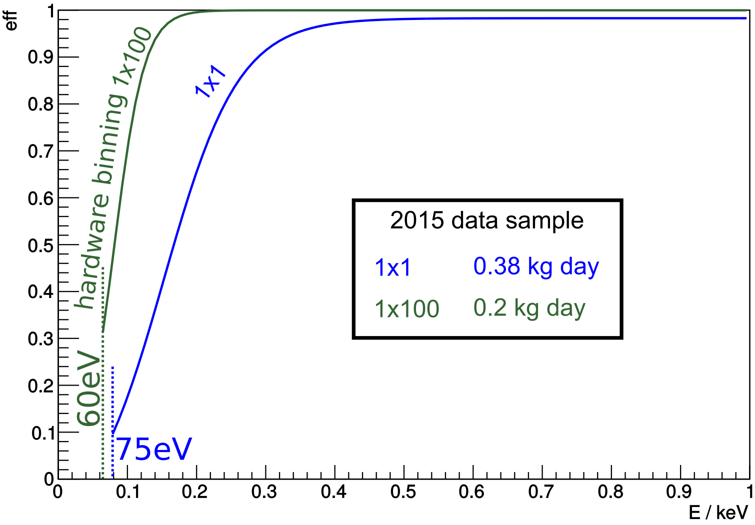
Data Analysis: exposure





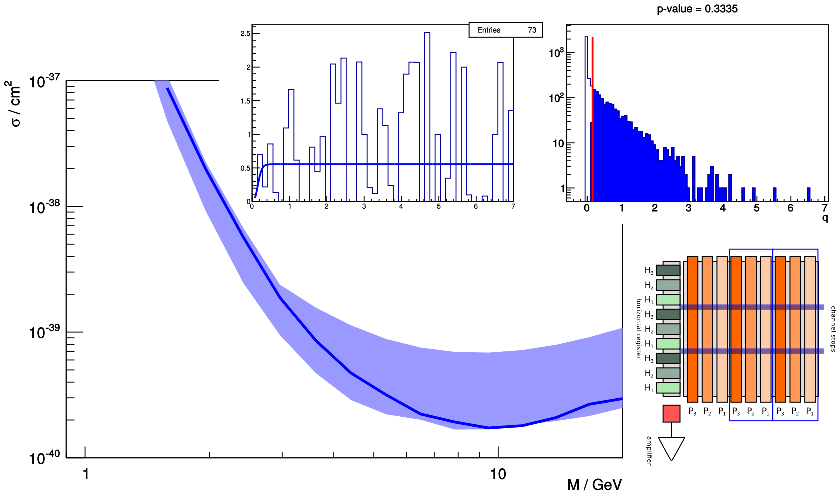
Simulation used to estimate the efficiency down to threshold.
Based on this efficiency, an exposure is calculated.

Efficiency



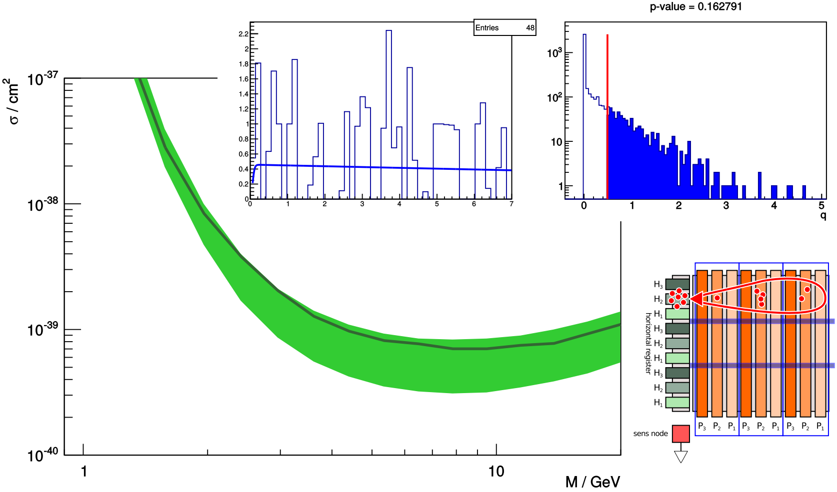
eff
E / keV
hardware binning 1x100
1x1
60eV
75eV
2015 data sample
1x1 0.38 kg day
1x100 0.2 kg day

1x1

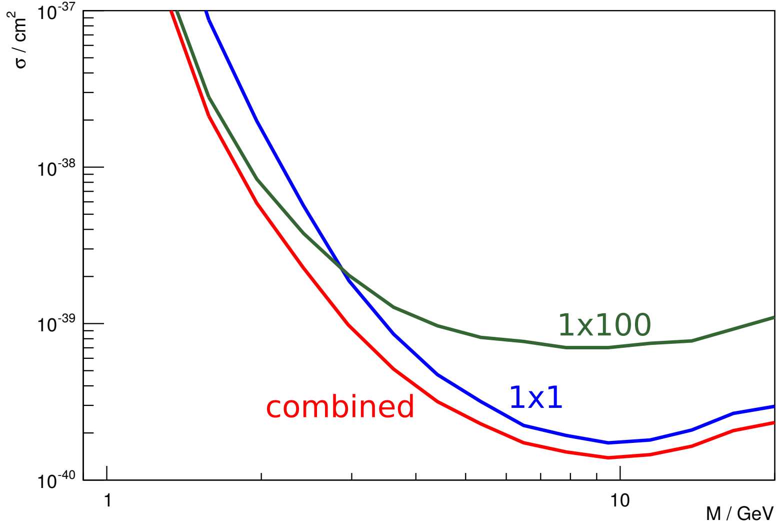


p-value = 0.3335
Entries 73
σ / cm²
M / GeV
q
horizontal register
channel stops
amplifier
H₃
H₂
H₁
P₃
P₂
P₁

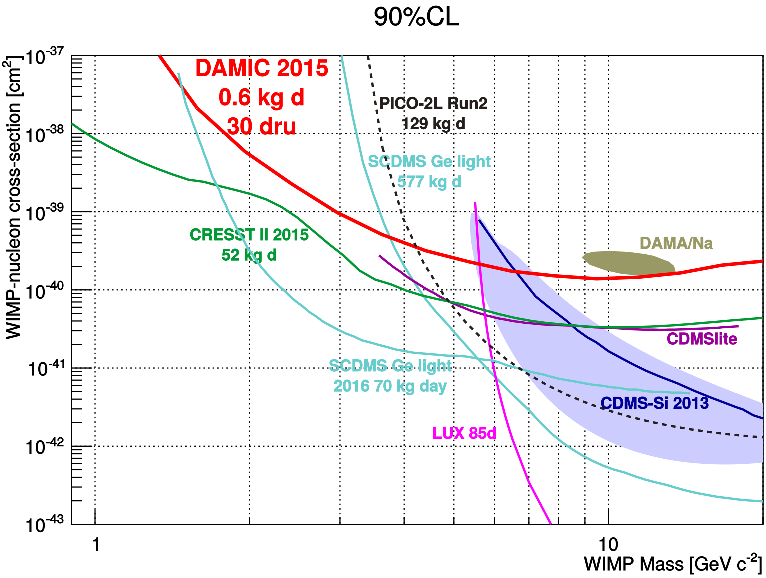
1x100 hardware binning



Limits

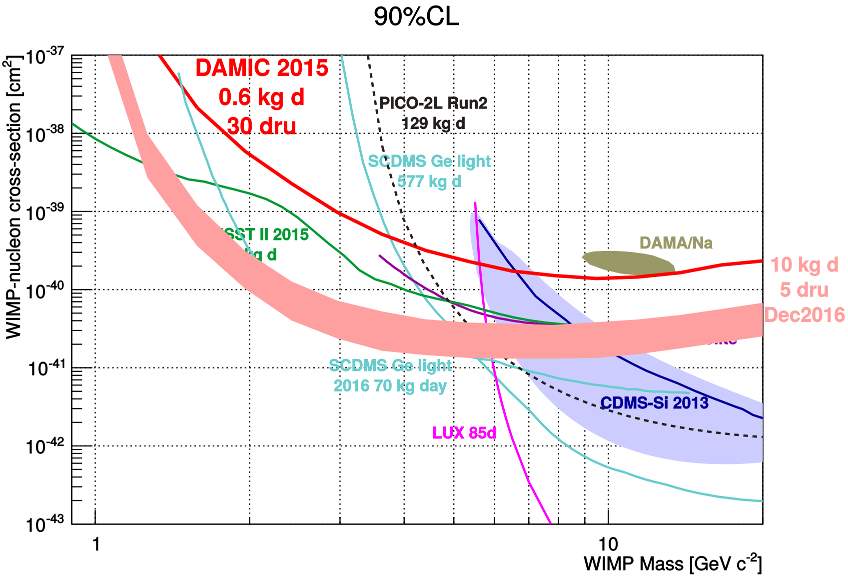


Limit

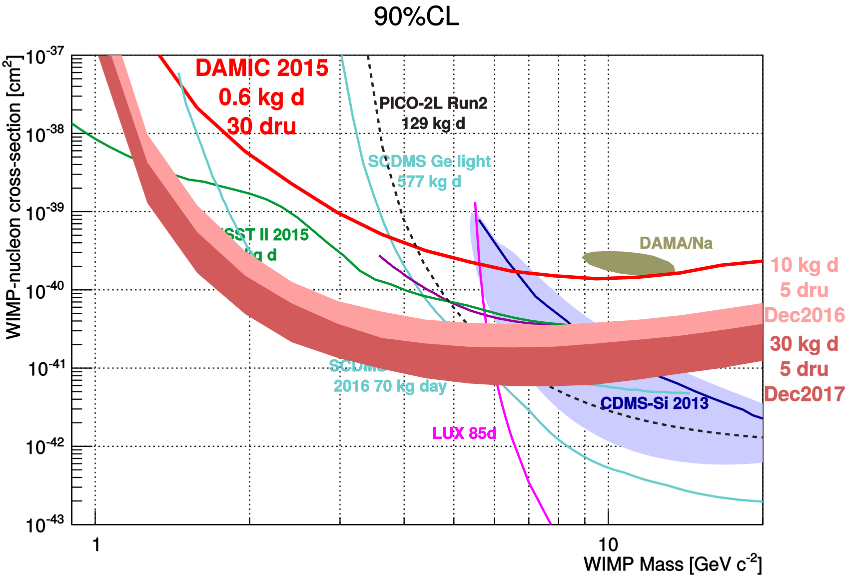


90%CL
DAMIC 2015
0.6 kg d
30 dru
PICO-2L Run2
129 kg d
SCDMS Ge light
577 kg d
CRESST II 2015
52 kg d
DAMA/Na
CDMSlite
SCDMS Ge light
2016 70 kg day
CDMS-Si 2013
LUX 85d
WIMP-nucleon cross-section [cm^2]
WIMP Mass [GeV c^{-2}]
10^{-37}
10^{-38}
10^{-39}
10^{-40}
10^{-41}
10^{-42}
10^{-43}
1
10

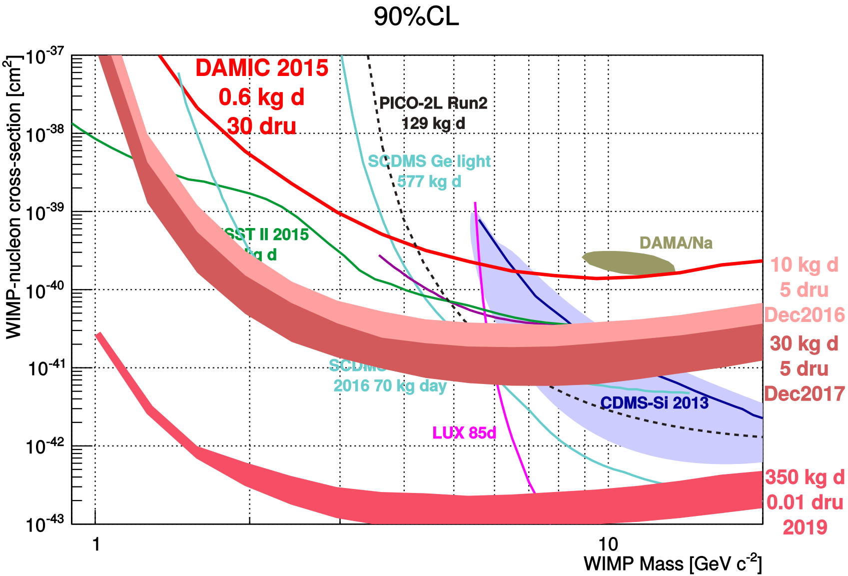
DAMIC100 reach



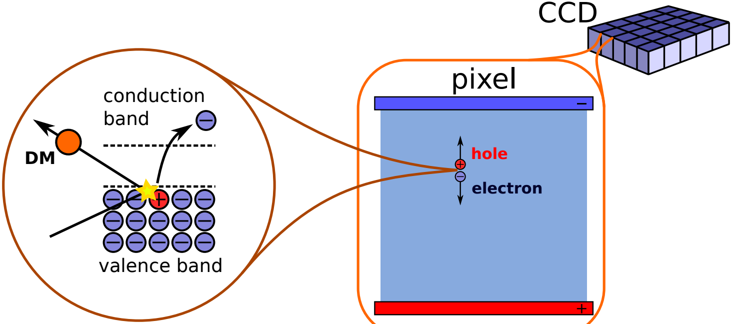
DAMIC100 reach



DAMIC100 reach

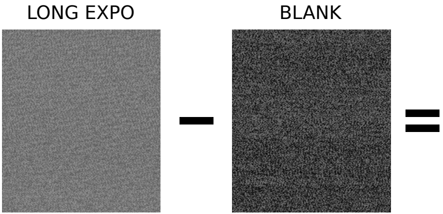


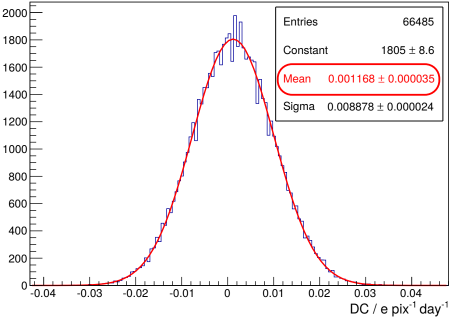
Electron recoil



Electron recoil

We can measure the Dark Current by looking at the “empty” pixels distribution after an extremely long exposure O(days)



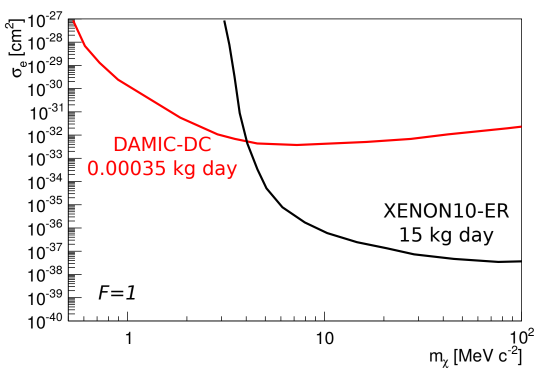


Measured Dark Current 0.001 e pix^{-1} day^{-1} (x10^{6} smaller than DES)
We can use this information to compute a limit on DM-e^{-} xsec.

Electron recoil

Looking for extremely low mass DM: world best limit

We can use the measured DC to compute a limit on DM-e^- xsec

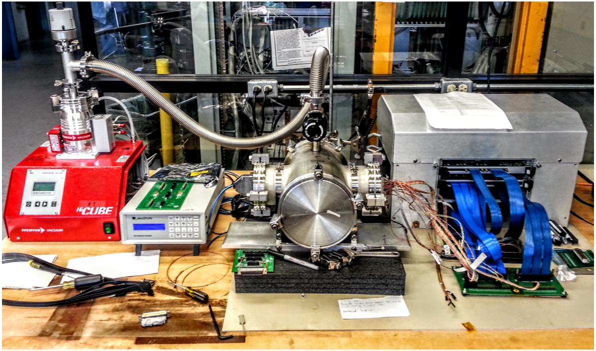


In collaboration with Jeremy Mardon (Stanford), Rouven Essig, Tien-Tien Yu (Stony Brook) and Tomer Volansky (Tel Aviv)

LDRD: Devt of an ultra low-energy threshold particle detector

Awarded proposal

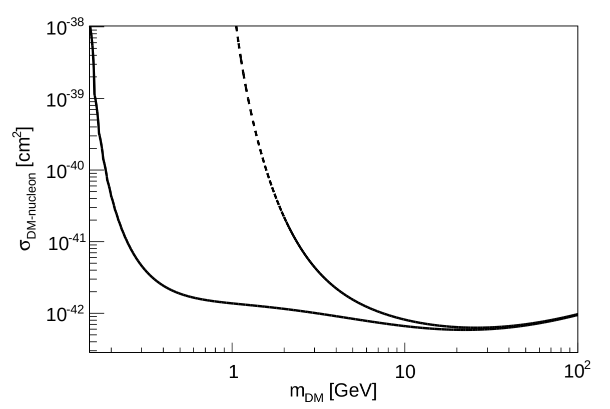
Develop a CCD-based detector with an energy threshold close to the silicon band gap (1.1 eV) and a readout noise of 0.1 electrons using a new generation skipper CCD developed by the LBNL MicroSystems Lab



Lowering the noise: Skipper CCD

Nuclear recoil sensitivity

Silicon-target WIMP search experiment with an exposure of 100 g year and no background (Skipper CCD and regular CCD)



Summary

- CCDs are an excellent candidate for detecting low energy DM events. The lack of mass is compensated by the low threshold.
- Nuclear recoil energy calibrated down to threshold
  - **deviation from Lindhard at low energy**
  - **using the correct model has a huge impact on the sensitivity**
- DAMIC operations at Snolab very reliable ($\sim$ 95% uptime)
- DAMIC100 in production mode. 10/18 sensors ready to deploy
- Electron recoil channel opens a new window to MeV scale DM
- **DAMIC100 commissioning in April 2016**

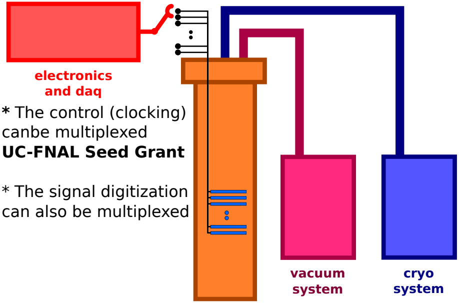
DAMIC Collaboration:

Fermilab, University of Chicago, University of Zurich, Snolab, University of Michigan, UNAM, FIUNA, CAB, UFRJ, University of Paris VI & VII

BACK UP SLIDES

DAMIC-1kg: readout electronics scaling

- we read the CCDs only a few times per day (or even less)
- we don't need to read all of them at the same time
  $\rightarrow$ **the readout and CCD clocking can be multiplexed**



***** The control (clocking) canbe multiplexed
UC-FNAL Seed Grant

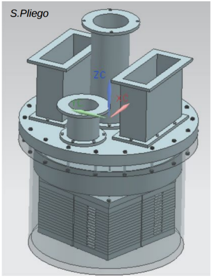
* The signal digitization can also be multiplexed

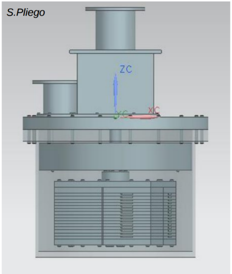
currently developing the technology

- Fermilab and Paris

DAMIC-1kg: mechanical design

- Cryogenics: CCDs operate at 100K. Commercial solutions available
- Shielding: need to minimize materials close to the CCDs
  - electronic connections could be a challenge

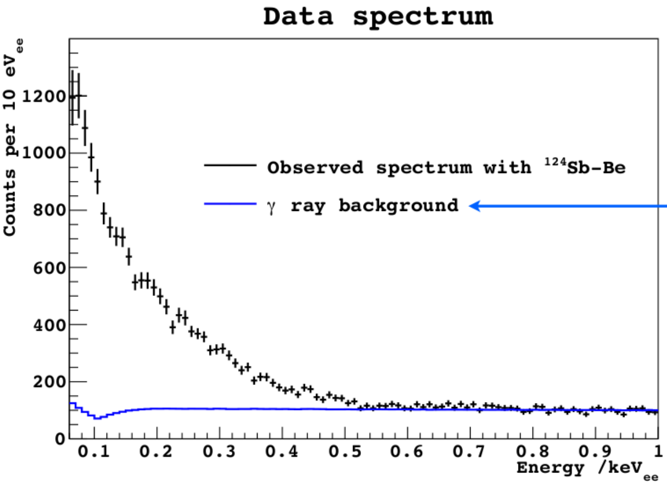




currently developing the technology

- UNAM: working on design concepts for the vessel

Nuclear recoil calibration



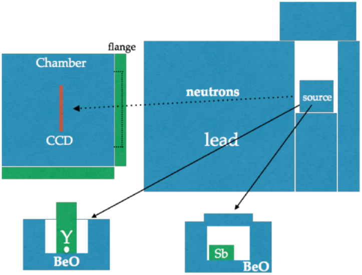
Normalized to count rate 2-5 keV$_{ee}$.

Uncertainty propagated in analysis.

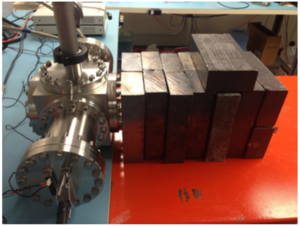
Quenching factor

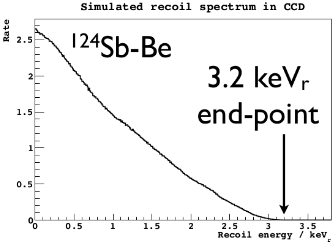
Neutrons

Fast neutrons from $^{9}Be(\gamma,n)$ reaction

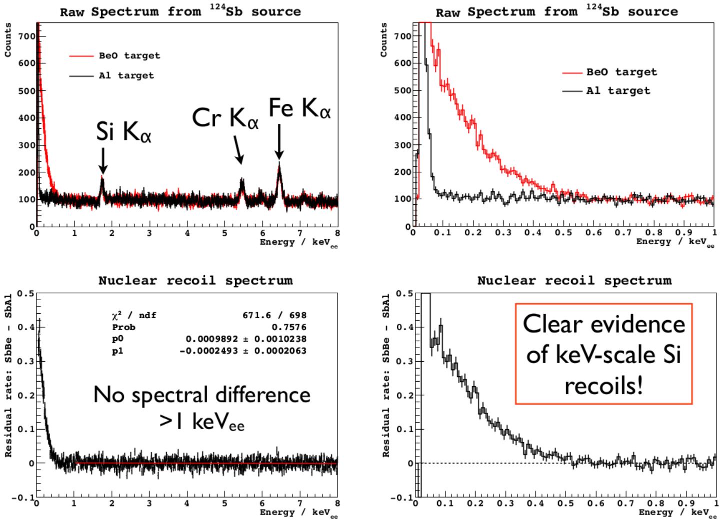


Neutrons from ^{124}Sb-Be source: **24 keV**



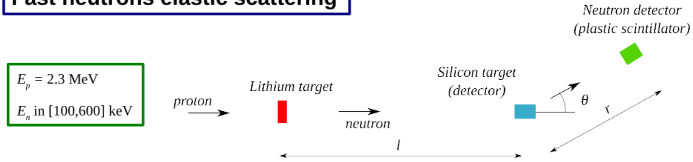


Quenching factor

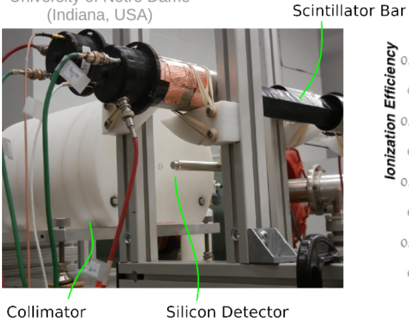


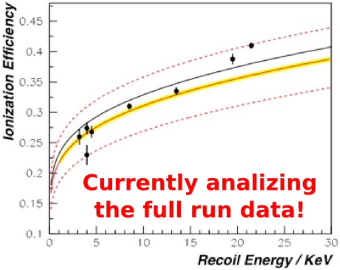
Quenching factor

Fast neutrons elastic scattering



University of Notre Dame
(Indiana, USA)

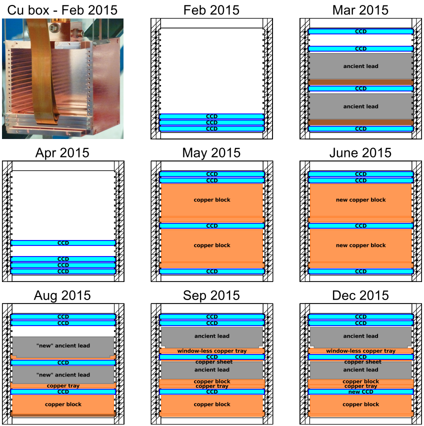




Intrinsic contamination of the CCDs

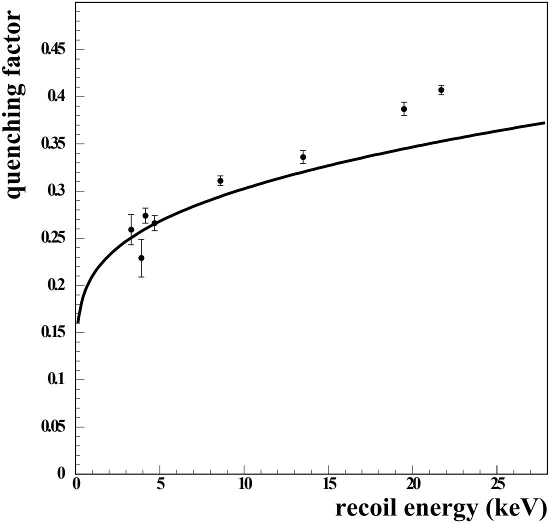
Analysis method	Isotope(s)	Tracer for	Bulk rate $\mathrm{kg}^{-1}\,\mathrm{d}^{-1}$
α spectroscopy	^{210}Po	^{210}Pb	<37
	^{234}U + ^{230}Th + ^{226}Ra	^{238}U	<5 (4 ppt)
	^{224}Ra – ^{220}Ra – ^{216}Po	^{232}Th	<15 (43 ppt)
β spatial coincidence	^{32}Si – ^{32}P	^{32}Si	110^{+150}_{-90}
	^{210}Pb – ^{210}Bi	^{210}Pb	<46

2015 campaign: tracking backgrounds



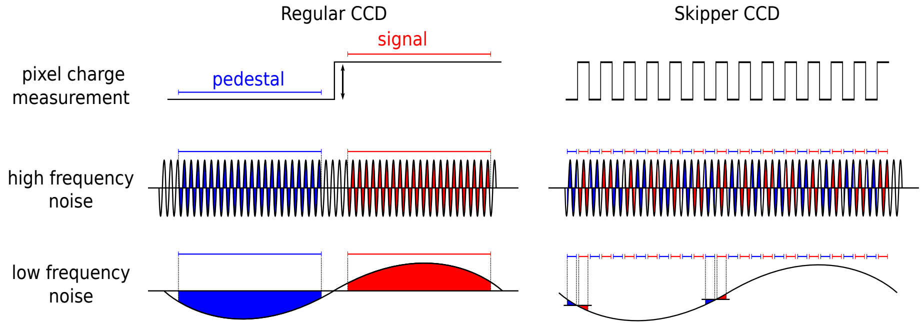
$\sim$80% of the time in low gain mode (high dynamic range) to identify backgrounds. Little time dedicated to science runs.

Quenching factor.

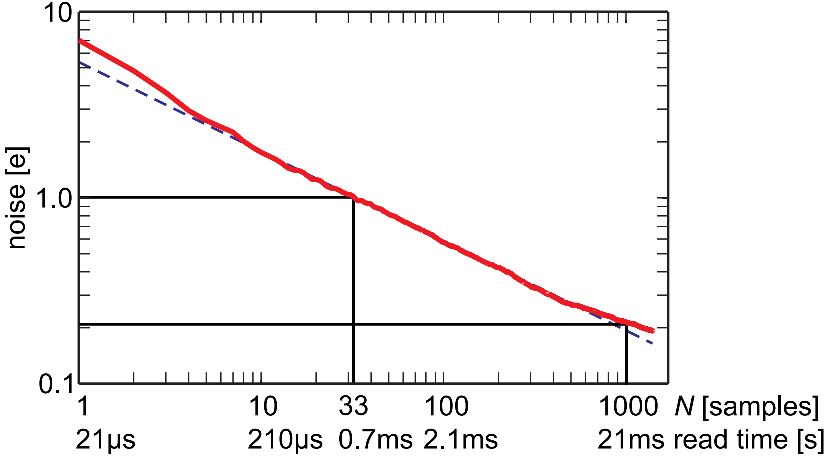


Lowering the noise: Skipper CCD

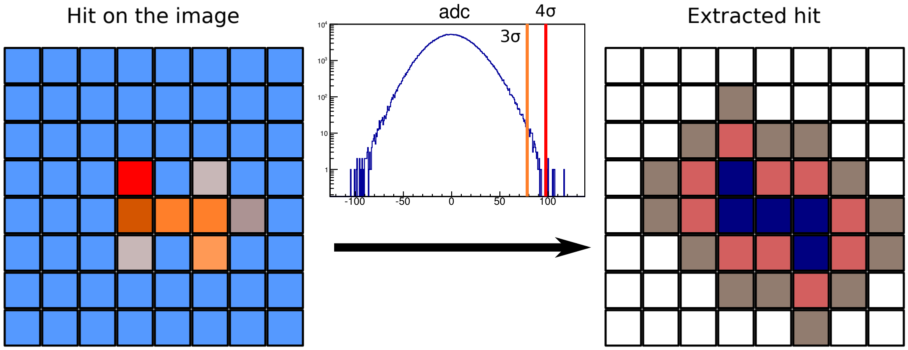
- Main difference: the CCD allows multiple sampling of the same pixel without corrupting the charge packet.
- The final pixel value is the average of the samples
  $$\textbf{Pixel value} = \frac{1}{N}\Sigma_i^N\,(\textbf{pixel sample})_i$$



Lowering the noise: Skipper CCD



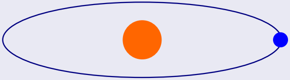
hit extraction

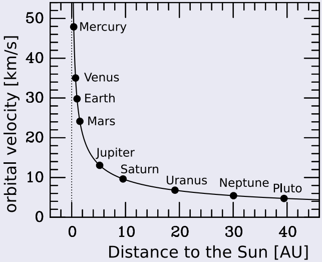


Observational evidence of Dark Matter (DM)

Luminous matter dominated

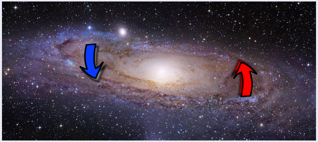
If the mass is concentrated, the orbital velocity falls as 1 over the square root of the distance.

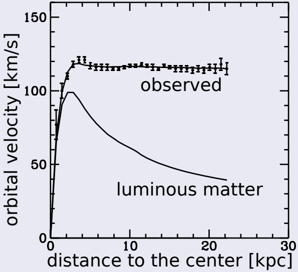




Dark Matter dominated

Measuring the shift in the spectrum one can calculate the speed of rotation

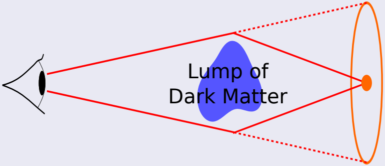




Observational evidence of Dark Matter (DM)

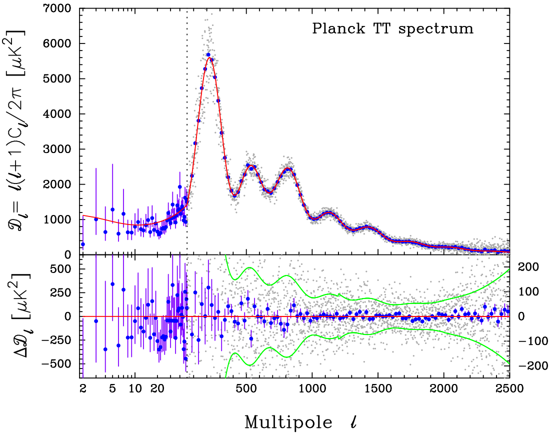
Bullet cluster

Gravitational lens



Observational evidence of Dark Matter (DM)

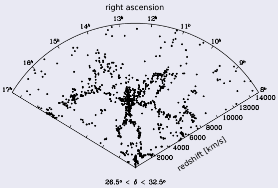
The autocorrelation seen in the background radiation is explained if one assumes that the amount of dark matter present is $\simeq 5.5$ times that of ordinary baryonic matter



Observational evidence of Dark Matter (DM)

Large-scale structure of the universe

The observed large-scale structure of the universe requires the presence of DM to form. DM is also necessary to understand the large-scale dynamics of galaxy clusters.



Nucleosynthesis in the Big Bang

The relative amounts of elements generated in the primordial nucleosynthesis depends on the density of the universe and the relationship between the amount of baryonic matter and photons.

The current explanation for the relative amount of ^{3}He and ^{7}Li observed requires the existence of dark matter.